Technological Forecasting & Social Change xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

Technology life-cycles in the energy sector — Technological characteristics and the role of deployment for innovation

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ARTICLE INFO

Article history:
Received 17 February 2015
Received in revised form 15 July 2015
Accepted 22 September 2015
Available online xxxx

Keywords:
Technology life-cycle
Energy technology
Patents
Citation-network analysis
Wind power
Solar PV

ABSTRACT

Understanding the long-term patterns of innovation in energy technologies is crucial for technology forecasting and public policy planning in the context of climate change. This paper analyzes which of two common models of innovation over the technology life-cycle – the product-process innovation shift observed for mass-produced goods or the system-component shift observed for complex products and systems – best describes the pattern of innovation in energy technologies. To this end, we develop a novel, patent-based methodology to study how the focus of innovation changes over the course of the technology life-cycle. Specifically, we analyze patent-citation networks in solar PV and wind power in the period 1963–2009. The results suggest that solar PV technology followed the life-cycle pattern of mass-produced goods: early product innovations were followed by a surge of process innovations in solar cell production. Wind turbine technology, by contrast, more closely resembled the life-cycle of complex products and systems: the focus of innovative activity shifted over time through different parts of the product, rather than from product to process innovations. These findings point to very different innovation and learning processes in energy technologies and the need to tailor technology policy to technological characteristics. They also help conceptualize previously inconclusive evidence about the impact of technology policies in the past.

1. Introduction

Technological change is "at once the most important and least understood feature driving the future cost of climate change mitigation" (Pizer and Popp, 2008, p. 2768]. A better understanding of the long-term patterns of innovation in energy technologies is therefore crucial for technology forecasting and public policy planning in the context of climate change (Grubb, 2004; Pielke et al., 2008; Grubler, 2014). Responding to this need, a growing body of literature is studying innovation processes and technology policy in the energy sector (Anadon, 2012; Gallagher et al., 2012; Grubler and Wilson, 2014).

It is a particularity of the energy sector that technologies from a diverse range of sectors of the economy are employed in the extraction, conversion, and end-use of energy. Therefore, most energy innovations are not developed by energy companies but enter the sector embodied in specialized equipment or innovative fuels from other sectors, such as semiconductors (solar panels), electro-mechanical machinery (gas turbines), agriculture (biofuel feedstocks), and biochemistry (biofuel conversion technology) (Markard, 2011; Wiesenthal et al., 2011). Empirical research suggests that long-term patterns in the process and focus of innovation, often referred to as 'technology life-cycles,' differ across these sectors, pointing toward the need to tailor government policies to individual energy technologies (Norberg-Bohm, 2000; Trancik, 2006; Wilson, 2012; Winskel et al., 2014).

However, thus far few studies of technological change in the energy sector have systematically investigated how technology life-cycles differ between energy technologies, and few have explored the implications for energy technology policy. To address this gap, we develop a patent-based methodology to analyze the technology life-cycles of solar photovoltaics (PV) and wind power. Solar PV and wind power differ in characteristics that have been linked to life-cycle patterns – the complexity of the product architecture and the scale of the production process – enabling us to derive propositions about technology life-cycles in energy technologies more broadly.

The paper proceeds as follows. Section 2 introduces two alternative models of the technology life-cycle – the product-process innovation shift observed for mass-produced goods and the system-component shift observed for complex products and systems – and discusses the main technological determinants of life-cycle patterns discussed in the literature. Section 3 introduces the two case technologies – solar PV systems and wind turbines – and discusses key technological characteristics and indicators of technological progress over the last five decades.

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http://dx.doi.org/10.1016/j.techfore.2015.09.022
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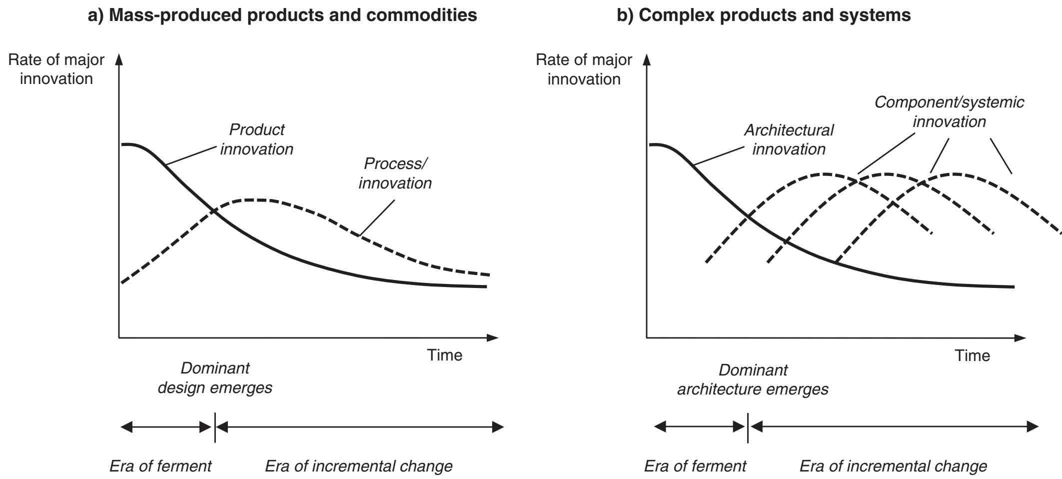

Fig. 1. Two contrasting models of innovation over the technology life-cycle: a) mass-produced goods; b) complex products and systems (Abernathy and Utterback, 1988; Davies, 1997).

In Section 4, we introduce a novel methodology to study how the focus of innovative activity evolved over time for the two case technologies. The results, which are presented in Section 5, suggest that solar PV and wind power followed very different technology life-cycle patterns. The implications for theory, public policy, and modeling practice are discussed in Section 6. Section 7 summarizes the main conclusions.

2. Theoretical perspective and literature review

The '*life-cycle*' metaphor has been used in many different contexts in research on the management and economics of innovation (Routley et al., 2013). This paper draws on the literature that uses the term life-cycle to describe the *temporal patterns* of *technological innovation* in an industry, in particular the emergence of dominant designs and the subsequent *shifts in the focus of innovation* (Utterback and Abernathy, 1975; Abernathy and Utterback, 1978; Abernathy and Clark, 1985; Suarez and Utterback, 1993; Murmann and Tushman, 2002; Murmann and Frenken, 2006; Lee and Berente, 2013).

2.1. Two contrasting models of the technology life-cycle

Studies across a wide range of manufactured products have observed that temporal patterns of innovation often take a cyclical form – the 'technology life-cycle' – with an early stage marked by intense competition among fundamentally different design concepts followed by gradual standardization of design features (Suarez and Utterback, 1993; Murmann and Frenken, 2006; Anderson and Tushman, 1990). After a *dominant design* has emerged, technological change becomes cumulative and incremental as innovation proceeds along ordered technological trajectories (Dosi, 1982; Mina et al., 2007; Verspagen, 2007; Fontana et al., 2009; Bekkers and Martinelli, 2012).

The most influential model of the technology life-cycle, which we will refer to as the Abernathy-Utterback (A-U) model, describes technological evolution cycles of *product* and *process* innovation (Utterback and Abernathy, 1975; Abernathy and Utterback, 1978; Suarez and Utterback, 1993; Vernon, 1966). According to the A-U model, the focus of innovation in the early years of an industry is on product innovation, as firms try to exploit the performance potential of the discontinuous innovation and compete in the market with many alternative product designs. This 'era of ferment' culminates in a dominant design as the technology's core components become standardized. What follows is an 'era of incremental change,' during which the focus of innovative activity is on process innovations and specialized materials, as firms sell into a mass market and compete primarily on the basis of costs — until a new discontinuity re-ignites design competition (see Fig. 1a). The shift from product to process innovations is enabled by the standardization of product design features, which facilitates a shift from small-batch production to mass production, and from general-purpose plants to large manufacturing facilities with highly specialized production equipment (see Table 1) (Abernathy and Utterback, 1988).

The A-U model has been extremely influential,[1] but researchers have noted that the model is valid only for a subset of technologies (Davies, 1997; Miller et al., 1995). In particular, empirical studies demonstrate that for many high-value, high-technology products there is no indication of a decline in product innovations over time (Lee and Berente, 2013; Gort and Klepper, 1982; Henderson, 1995). These *complex products and systems* never reach a phase of process innovation and large-scale production for a mass market. Rather, firms sell to a relatively small set of customers and innovative activity remains focused on product innovation throughout the life-cycle (see Table 1) (Davies, 1997; Hobday, 1998; Davies and Hobday, 2005).

Based on this evidence, Davies (Davies, 1997) introduces a model of innovation over time that replaces the product-process shift observed for mass-produced goods by a shift from innovation in the system architecture to waves of innovation in sub-systems and components (see Fig. 1b) (Davies, 1997; Davies and Hobday, 2005). As in the A-U model, the early phase is characterized by a focus on functional performance and product innovations. However, the competitive emphasis is not on specific designs but on alternative *product architectures*. After the emergence of a dominant design (constituted by a common product architecture and standardized core sub-systems), innovation along the technological trajectory is focused on individual sub-systems and components (Murmann and Frenken, 2006).[2] Over time, innovations in sub-systems and components can create performance imbalances that require changes in other parts of the system (Brusoni et al., 2001; Funk, 2009), in which case Davies refers to them as '*systemic innovations*' (see Fig. 1b).

The two models differ most significantly in their characterization of the era of incremental change, i.e., the incremental change along the technological trajectory after a dominant design has emerged (see Table 1). Three aspects are particularly important: First, with regard to the *type and breadth of innovative activity*, the A-U model predicts a surge in process innovations and a relatively narrow focus on cost reductions through improved production processes. The Davies model, in contrast, describes a steady stream of product innovations as well

[1] The two seminal works (Utterback and Abernathy, 1975; Abernathy and Utterback, 1978) had, as of 12/6/2014, a total of 6544 Google Scholar citations between them.

[2] For example, after the emergence of the turbojet engine as the dominant propulsion system, innovative activity in the aircraft industry focused on improving the airframe and parts of the engine, such as compressor blades, rather than shifting toward process mechanization and automation (Hatch and Mowery, 1998).

Please cite this article as: Huenteler, J., et al., Technology life-cycles in the energy sector — Technological characteristics and the role of deployment for innovation, Technol. Forecast. Soc. Change (2015), http://dx.doi.org/10.1016/j.techfore.2015.09.022